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LIGHTNING PROTECTION DESIGN AND TESTING OF AN ALL COMPOSITE WET WING FOR THE EGRETT

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1 INTRODUCTION

The Egrett aircraft, made by Grob of Germany, has an all composite wing comprising CFC/Nomex sandwich skins, full length CFC main spar caps and GFRP main and auxiliary spar webs. It also has short inboard CFC auxiliary spar caps. It has fine aluminium wires woven into the surface for protection. It has an integral fuel tank using the CFC/nomex skins as the upper and lower tank walls, and lies between the forward auxiliary spar and the forward of the two main spar webs. The fuel tank is not 'bagged', ie it is in effect a wet wing tank. It has conventional capacitive type fuel gauging.

The aircraft has been cleared to IFR standards and so required full lightning protection and demonstration that it would survive the lightning environment. Grob Aircraft Company, with Culham Lightning Test and Technology as consultants, designed the lightning protection for the wing (and also for the remainder of the aircraft). An inner wing test sample (which included a part of the fuel tank) was tested at the Culham Lightning Simulation Laboratory as part of the proving programme. This paper describes the protection design, the testing process and indicates the intrinsic structural features that improve lightning protection design and which therefore minimise the weight and cost of any added lightning protection components.

The design and testing procedures must meet the requirements of AC20-53A(1) for fuel systems for aircraft.

2 BASIC WING DESIGN LIGHTNING CONSIDERATIONS

The wing cross section is shown in Figure 1, where the construction, comprising CFC/Nomex, CFC spar caps, and glass fibre reinforced plastic (GFRP) spar webs, is fully cocured and bonded, and virtually no fasteners are used. The only metallic components originally in the design were the fuel gauge wires (A), the aileron operating rod (B), a drive cable for the flaps (C), electric wires to the wing tip light, Pitot and other wing mounted electrical items (D), and fuel and vent pipes (E). Item (C) only runs a very short distance along the wing (there are only inboard flaps) and fuel gauge wiring ran only as far as the outer-most gauge, about half way along the wing. Apart from these, the main components of the wing which would carry lightning current would be the main spar caps which are solid 0° carbon lay up, and to a less extent the skins, but these were very thin. Inboard, the CFC spar caps of the auxiliary spars could in principle carry current. (The auxiliary spar caps were shown later on to be completely insulated from the rest of the wing and so played no part in lightning protection.)

The hazards from lightning can be divided into three main areas:

a) structural damage (excluding fuel explosions) to the wing affecting flight safety.
b) fuel vapour explosions in or around the tanks and pipes.
c) excessive induced voltages causing (b) or damaging the aircraft electrical system.

Apart from some tests on 'coupon' samples of the wing skins and fuel tank access doors, the remainder of the lightning protection design evolved by detailed consideration of the wing design, so making optimum use of the wing structure for protection.

3 PROTECTED WING DESIGN AS TESTED

3.1 Examination of the fuel tank design together with the results of the coupon tests suggested that the tank was unlikely to spark as a result of Zone 3 conduction currents or swept stroke 2A/2B attachment to the wing. However, because of the novel features of the design, a simple similarity argument could not be made, and there were also three possible sparks site zones which could only be qualified by test. Two of these are shown in Figure 2 and involved first, possible sparking at the inboard close-out of the tank, and secondly at a bonded panel in the undercarriage bay area of the tank. (The third one is associated with the fuel gauge systems and will be discussed later.) Sparking at the fuel tank access doors had already been shown to be absent from coupon tests to the door and its immediate surround, so this was not to be considered during the main tests. Camera and fibre optic light sensors were placed in the wing as shown in Figure 3 in order to specifically cover the identified sites, but to cover the whole tank as well.

The tests showed that with both Zone 3 and Zone 2A/2B tests, no sparking occurred in the tank area. This conclusion required very close attention to the test details since a lot of stray light leaked in through partially transparent GFRP in areas of the tank not covered by opaque sealant.

3.2 Fuel and vent pipes for tank. To avoid problems with these, low electrical conductivity "static dissipating" pipes were used to prevent the risk of current flow in them and so to prevent sparking at joints, etc.

3.3 Fuel gauge wiring. As previously discussed, the fuel gauges contribute a potential fuel ignition hazard owing to the possibility of sparking between the fuel gauges and the CFC skins locally. This depends upon the magnitude of the voltage generated by current flow in the wing material and the insulation level at the gauge. The magnitude of voltage generated in the fuel gauge wiring is determined critically by the position of the wires in relation to good conducting structure, in this case being the mass of 0° CFC comprising of the main spar caps (see Figure 1). Modifications to wiring positions were made both externally, where it was recommended that the wiring outside the wing was screened, and inside, where it was demonstrated that voltages could be brought low enough by careful positioning of the fuel gauge wires right in the corner of the spar cap/spar web as shown in Figure 1, where (a) shows the original position and (b) the improved position. The measurements shown in Table 1 demonstrated the advantage of careful use of structure and wiring location. The original configuration voltage (extrapolated to 'full threat') was 3440 resistive volts and 18kV inductively generated voltage, reducing to 2600 resistive and 4.6kV inductive after the modification. No added material was needed within the wing to secure this improvement, only repositioning of the wiring tight within the corner of the spar cap/web. The reduction in inductive voltage (ie, the component of voltage proportional to di/dt) is very marked, and suggests that di/dt coupling occurs along part of the wing internally; probably in the region between the undercarriage bay and the wing root where the skin is presumably insulated from the main spar caps as well as from the auxiliary spar caps. Evidence for this was the reduction in di/dt voltage when the skin was joined to the spar cap at the root by the add on copper sheets.

With adequate insulation at the fuel gauges, the induced voltages will be insufficient to cause sparking and therefore no fuel ignition.

3.4 Induced voltages in wing tip and Pitot wiring. The wiring runs from the wing tip light and from a Pitot tube well out on the wing to the wing root. Insulation is not practical for the system, and the risk of a very high current injection into the aircraft electrical system is very serious unless precautions are taken. The protection method is an aluminium tube running the full length of the wing in an electrically continuous length, bonded to the light surround at the outer edge and to the fuselage ground plane at the inner, with the wires inside. By this method, almost complete elimination of the induced voltage occurs except for a residual resistive voltage resulting from current flow in the tube. This was proved by the test in which the current along the tube, and the voltage inside were measured during a current pulse to the wing, and shown to be in Ohm's law agreement with the tube current and resistance, ie, the current pulse of 67k amps max produced a voltage of 200V in a tube of $3m\Omega$.

The presence of the tube has an effect on current flow in the wing, especially at late times during the pulse as shown in the following section.

3.5 Current sharing and current waveforms in wing bonding components. Table 2 shows the current distribution between the various connections to the wing at the root end, these tests were made mainly using oscillatory pulses of approximately 50kA peak. This table shows that the forward and rear auxiliary spars are not in electrical contact with the wing, so the lightning current is taken only by four components; upper spar, lower spar, aileron rod, and the lightning protection tube in the ratio of 30%, 39.5%, 17%, 13.5%. However tests with a unidirectional Component A pulse through the whole of the wing sample produced a current pulse in the tube like Figure 4 of 1280μs long compared with the Component A current pulse of approximately 460μs total length.

The tube current rose to 67kA at 216μs after the start of the pulse and had a very flat top, at which time the Component A current pulse was only 50kA; ie, the tube current was larger than the applied current pulse, since an eddy current had been established in the wing between the CFC and the metal.

This is a familiar phenomenon with CFC structures incorporating high conductivity components such as a metal tube.

4 COMMENTS ON DESIGN OF WING/FUEL TANK AFFECTING CERTIFICATION FOR LIGHTNING

In Section 2 of this paper, 3 types of potential hazard were mentioned as being specifically applicable to CFC structures. The first was structural damage affecting flight safety resulting from an attachment. Tests carried out prior to and during this test procedure (but not reported here) showed that the CFC/Nomex/CFC material, with aluminium wires in the outer ply is virtually unaffected by Zone 2A lightning attachments apart from minor tufting at the the arc attachment points. Owing to the absence of metal components there are no current concentration points to cause direct effects damage to the wing away from the arc attachment point either, so making it safe.

The second hazard was fuel vapour ignition from sparking within the tank. Tests on coupons had previously verified that Zone 2A attachments to the fuel tank access panels did

not cause sparking within the tank, and tests at Culham prior to the main test using an infra-red camera had shown that Zone 2A attachments to the fuel tank upper or lower skin material gave a temperature rise in the inside tank wall of no more than 87°C, which is safe.

The tests reported here have shown that no sparking occurs within the tank from conduction tests (Zone 3) at 200kA or with Zone 2A attachments to the wing skin (near the undercarriage bay). The design features of special significance here are that there are no fasteners used in the tank region; it is a fully bonded structure with CFC/Nomex upper and lower skins and glass fibre forward and rearward walls. The CFC skins are unjointed in the tank region, since the forward GFRP auxiliary spar protects the tank from possible sparking at the upper skin/lower skin bond line at the leading edge shown as Point A in Figure 1.

Although some light was observed in the tests, careful exploratory work showed that it was light leaking through the semi transparent GFRP from minor sparking elsewhere, probably in the region *aft* of the main spar, and also at the root end, where external surface sparking occurred at the wing skin/spar joint prior to the addition of the copper sheet referred to in Section 3.3. Light leaks in the structure incorporating fibre-glass are a severe problem in achieving a satisfactory optical test for sparking. It would, in principle have been possible to use an ignitable gas test but the provision of adequate blow-out panels would have been very difficult in such a large volume, and the damage resulting from a mis-test would have stopped the test programme owing to a shattered test specimen.

The other principle problem concerning lightning in a CFC wet wing is excessive induced voltage either in the fuel gauge wiring causing sparking in the fuel tank or large induced or injected currents in other wiring which can damage aircraft power systems, etc. As discussed in Section 3.3 wiring can be protected by routing and insulation where all the wiring and the items to which it is connected are *totally inside* the structure and not subject to direct attachment, as indeed for the fuel gauge wiring. (The use of conduit inside a fuel tank is *very unsatisfactory* owing to the sparking problem at its bonding points, and the same problem applies to any other form of shielding. Conduit which is grounded one end only or which has an insulation break in it does not reduce the magnitude of the voltage available and therefore does not prevent over voltage sparks at the gauge units.) In the Egrett design, protection is obtained by optimum routing and adequate insulation at the gauge transmitters.

Wiring to Pitots, stall warning devices, navigation lights can not be protected in this same way since they risk a direct lightning attachment. For this the Egrett design uses an aluminium tube which is bonded to structure and to the light surround to carry the wiring all the way into the fuselage. This method minimises the voltage induced in the wiring, and reduces them to a tube resistive voltage only as explained above.

5 CONCLUSIONS

The Egrett wing design achieves lightning protection by a combination of aluminium wire skin protection in the outer ply of the CFC/Nomex/CFC structure, a no-fastener design including an all-bonded fuel tank structure, and low induced voltages by a) choice of locations of the fuel gauge wiring and b) by use of a light weight tube for the wing tip navigation light. A few bond straps are also required to complete the protection together with inboard wire screens for the wiring connection to fuselage items.

Lightning protection of composite aircraft can be achieved, and the aircraft certificated with minimum increase in weight if due care and attention is given to details. The assistance of experienced consultancy is essential well before certification is to take place, and preferably at the detailed design phase, so that low weight techniques can be

incorporated to solve the lightning problems. Lightning is potentially a very severe environmental hazard to composite aircraft, but good design can minimise the weight and cost penalty of achieving protection.

ACKNOWLEDGEMENTS

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REFERENCES

1. FAA Adviser Circular AC20-53A. Protection of Airplane Fuel Systems against Fuel Vapour Ignition due to Lightning. 1985.

TABLE I
FUEL GAUGE VOLTAGE EXTRAPOLATED FROM ~50kA TO 200kA, 140kA/µs

SHOT NO.	PEAK TEST CURRENT kA	EXTRAPOLATED VOLTAGES $\propto I$	$\propto di/dt$	EXTRAPOLATED LESS EXTERNAL di/dt	COMMENTS
1	50	3.4kV	22kV	18kV	Original route
2	50	3.4kV	22kV	18kV	Revised external route
3	50.5	2.96kV	11.9kV	7.9kV	Revised internal route
4	52	3.1kV	7.7kV	3.9kV	As 3) but copper added spar/skin (upper)
5	50	2.6kV	8.6kV	4.6kV	As 4) but copper added to spar/skin (lower)
6	48.5	3.1kV	10.7kV	6.7kV	Contact moved to 1L
7	47	2.4kV	9.0kV	5.0kV	Contact moved to 2U

TABLE II
CURRENT SHARING AT WING ROOT BONDING POINTS

BOND POSITION	MEASURED CURRENT kA	EXTRAPOLATED TO 200kA KA	%
Main Upper Spar	14.7	60.6	30
Main Lower Spar	20.0	80.2	39.5
Lightning Tube	6.95 67.6(1)	27.9 73.0(1)	13.76 *(1)
Aileron Bond	8.5	34.1	16.8
Forward Auxiliary Spar	0	0	0
Rear Auxiliary Spar	0	0	0

All tests at ~50kA oscillatory except (1) using a 200kA Component A unidirectional Pulse. The % current reached was 36.5% of the initial peak current, but it occurred 216µs after the initiation of the current pulse, at which time it was greater than the applied pulse.

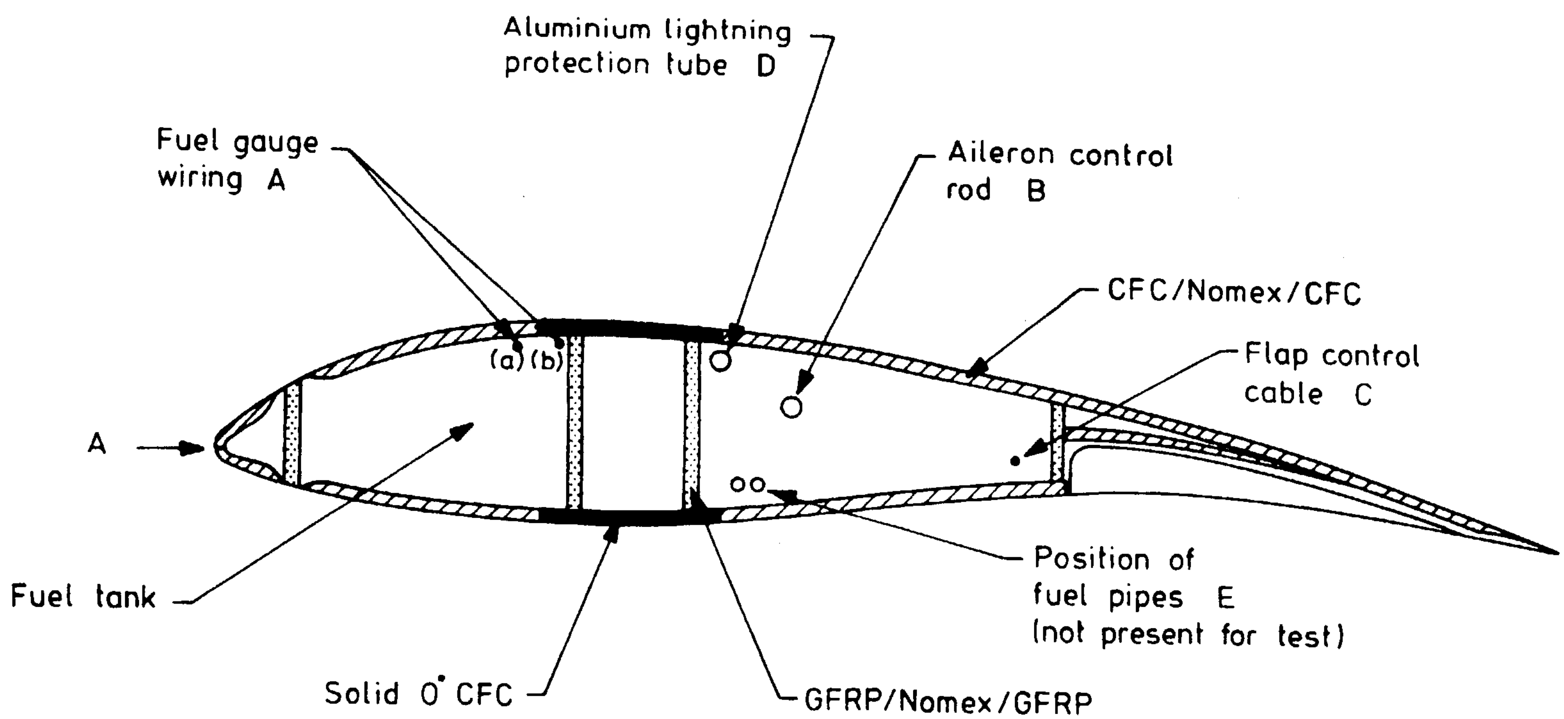


Fig 1 Cross section of wing tank test specimen

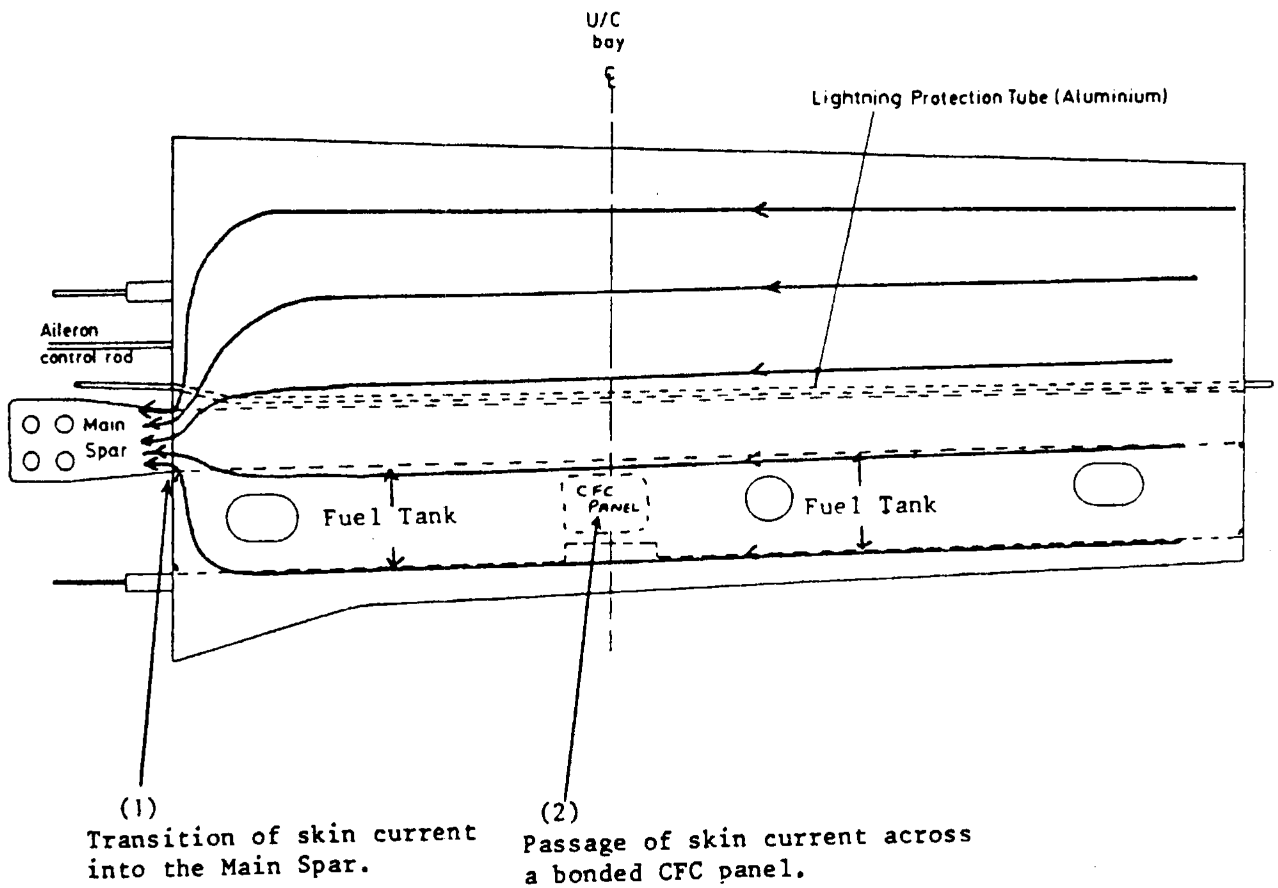


Fig 2 Top view of wing tank specimen showing possible sparking sites.

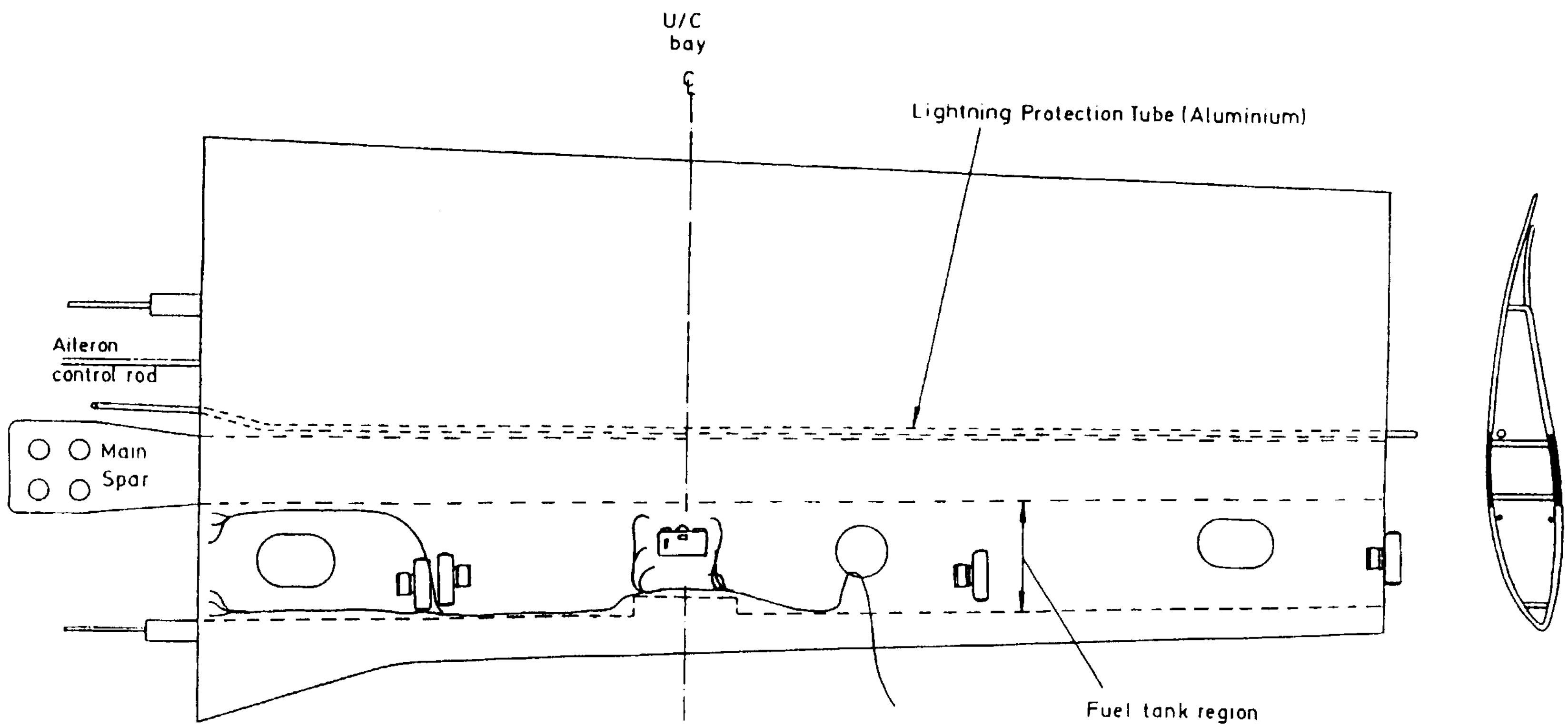
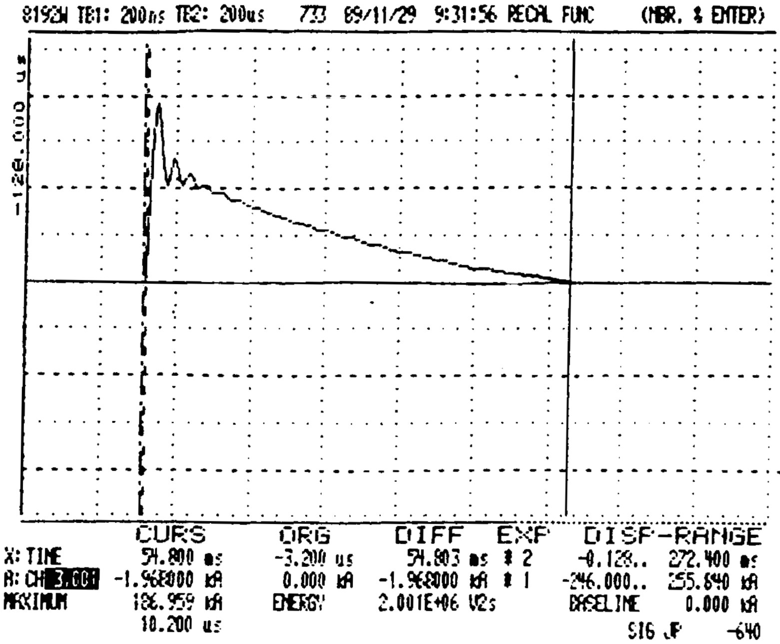


Fig 3 Fibre optic and camera layout for sparking observations.



Component A current pulse

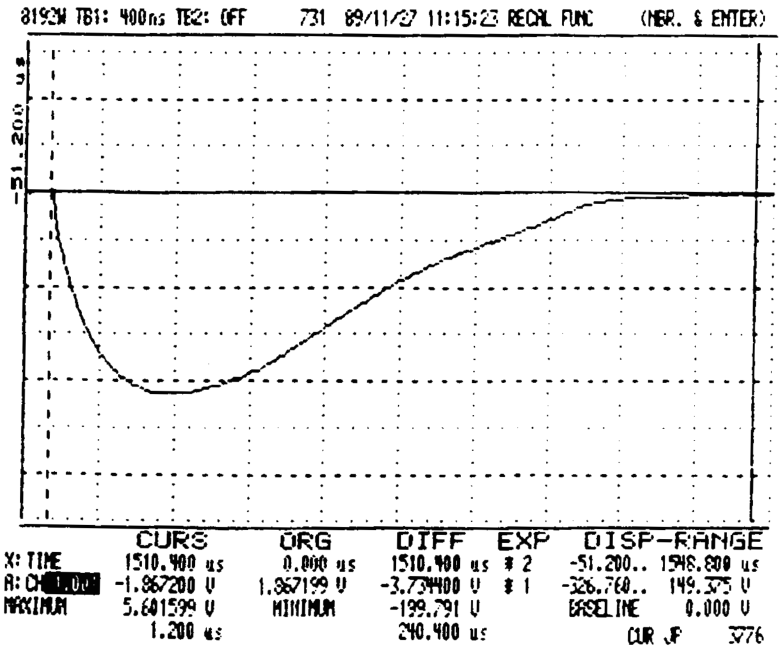
$\hat{I}$ = 187kA, AI = 2 x 10^6 A^2s

H: 80μs/cm

V: 49.2kA/div

(Shot 4377)

1 division



Voltage induced in WLPT

(fuselage region screened)

Component A.

H: 160μs/cm

V: 46.7v/div

Fig 4 Total current in wing (upper) Current and voltage waveform in Lightning protection tube

Total pulse duration 460μs

Total pulse length 1280μs.